

MINERALOGICAL INVESTIGATION OF DECAY OF SANDSTONE
AS BUILDING MATERIAL AT KUSUM SAROVAR, MATHURA

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the degree of

MASTER OF TECHNOLOGY

by

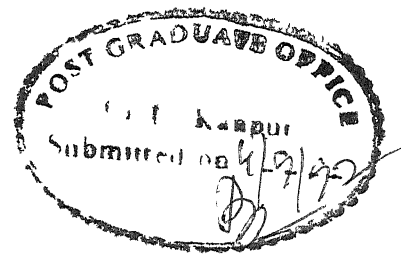
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to the

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

SEPTEMBER, 1992

CERTIFICATE



This is to certify that the present work, entitled "Mineralogical Investigation of Decay of Sandstone as Building Material at Kusum Sarovar, Mathura" has been carried out by Mr. Nehmani under my supervision and the same has not been submitted elsewhere for a degree.

A handwritten signature in cursive script, reading "Bikash C. Raymahashay".

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ABSTRACT

Among building stones, sandstone is a relatively durable rock mainly because its high quartz content makes it resistant to weathering. On the other hand, the detailed study of sandstone structures at the ancient Kusum Sarovar Complex, built in the 18th Century, near Mathura showed signs of decay. Mineralogical investigation of samples collected from the site as well as from the quarry near Bharatpur which supplied these rocks, indicated that the main weathering reaction is kaolinisation of K-feldspar present with an average feldspar to quartz ratio of 1:2. Laboratory measurements showed that apparent specific gravity decreased, and water absorption and apparent porosity increased from relatively fresh to more weathered rock. The degree of weathering was quantified through a computer based weathering model which gave weathering index $X_d = 0.22$ to 0.38 on a $0 - 1$ scale. A comparison with Khondalite through a similar weathering model indicated that this sandstone is much less weatherable.

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CHAPTER 1

INTRODUCTION AND OBJECTIVE

Locally available rocks have been widely used as building materials in ancient times. The most important characteristics of building stones are texture, colour, weatherability and ability to take polish. The durability of stones depends on the constituent minerals and their interaction with a complex group of natural and man-made weathering agents. Hence, it is important to go into the fundamental aspect of decay of minerals in a natural building stone. This information is very important for conservation purposes.

This study was concerned with decay of sandstone used as building material at Kusum Van Sarovar Complex, near Mathura (U.P.). From the local geology, it was concluded that this sandstone belongs to Precambrian Aravalli - Delhi sequence (Pascoe, 1965). More detailed description of this rock is given in subsequent chapters.

In India, a whole range of excellent building stones occur mainly in the Precambrian terrain of South and Central India. Table 1.1 summarizes the locations of the common building stones of India.

The most important engineering properties of building stones are their strength parameters like uniaxial compressive strength, tensile strength etc. A few representative values of Indian rocks are given in Table 1.2.

The effect of water saturation on strength was studied by Seshgiri Rao et al. (1981). Their results are given in Table 1.3.

However, for study of weathering of building stones, chemical composition and mineralogy are perhaps more relevant parameters. Raymahashay (1989) concluded that common building stones fall into two categories. These are (1) calcareous (calcite rich),

TABLE 1.1 : BUILDING STONES OF INDIA.

Modified from Sharma (1991). Original data from
Chatterjee (1960) and Krishnan (1982).

ROCK TYPE	LOCATION
1. MARBLE	Alwar, Jodhpur, Mewar (Rajasthan). Jabalpur, Betul, Chindwara, Narasinghpur (MADHYA PRADESH). Baroda (GUJRAT).
2. LIMESTONE	Mirzapur (UTTAR PRADESH) Hazaribagh, Manbhaum, Ranchi (BIHAR). Tuticorin, Coimbatore (TAMIL NADU). Bisra, Rourkela (ORISSA). Hushiarpur (PUNJAB). Udaipur (RAJASTHAN). Simla (HIMANCHAL PRADESH).
3. GRANITE	Kistna, Nellore, Secundrabad (ANDHRA PRADESH). Balaghat, Chindwara, Bhandara (MADHYA PRADESH). Ranchi, Hazaribagh, Gaya (BIHAR). Kamara, Belgaun (MAHARASTRA). Dalhousi, Kangra (HIMANCHAL PRADESH). Bundelkhand (U.P./M.P.).
4. BASALT	Bombay (MAHARASTRA). Rewa, Dewas (MADHYA PRADESH). Santhal Parganas (BIHAR).
5. SLATE	Dehradun, Ranikhet (UTTAR PRADESH). Simla, Kangra (HIMACHAL PRADESH). Gurudaspur, Attock (PUNJAB). Bijapur (KARNATAKA).

ROCK TYPE

LOCATION

6. SANDSTONE Mirzapur, Chunar, Agra (UTTAR PRADESH).
 Jabalpur, Raipur, Gwalior (MADHYA PRADESH).
 Cuttack, Sambalpur (ORISSA).
 Manbhaum, Ranchi (BIHAR).
 Delhi
 Bansipaharpur (RAJASTHAN).

TABLE 1.2 : STRENGTH PROPERTY OF INDIAN ROCKS.

Adopted from Madhav (1980)

ROCK TYPE	COMPRESSIVE STRENGTH (kg/cm ²)	TENSILE STRENGTH (kg/cm ²)	YOUNG'S MODULUS×10 ⁵ (kg/cm ²)
GRANITE	1600 - 3000	300 - 570	1.2 - 8.0
BASALT	800 - 400	. . . . .	. . . . .
LIMESTONE	350 - 2700	. . . . .	3.0 - 8.4
SANDSTONE	300 - 2400	70 - 200	1.0 - 5.4
GNEISS	1500 - 2500	. . . . .	. . . . .
MARBLE	450 - 2500	. . . . .	. . . . .
DOLOMITE	600 - 3600	. . . . .	. . . . .

TABLE 1.3 : EFFECT OF MOISTURE ON STRENGTH

From Seshgiri Rao et al (1981)

ROCK TYPE	COMPRESSIVE STRENGTH			TENSILE STRENGTH		
	(kg/cm ²)			(kg/cm ²)		
	DRY	SATURATED	%CHANGE	DRY	SATURATED	%CHANGE
SANDSTONE						
1. JHARIA	-	-	-	216	193	12
2. QUARTZITIC	580	290	50	-	-	-
GNEISS						
1. GRANULITE	1542	838	45	-	-	-
2. QUARTZITIC	2615	2096	20	-	-	-
MARBLE	-	550	-	41	27	33
BASALT	1085	1041	04	-	-	-
GRANITE - 1	1208	1058	12	-	-	-
GRANITE - 2	-	-	-	108	94	13

and (2) siliceous (quartz or silicate - mineral rich). For example, marble belongs to the first category and sandstone to the second category the decay of marble is usually related to the congruent dissolution of calcite under the attack of natural and man - made acids like H_2CO_3 , H_2SO_4 , HNO_3 etc. On the other hand, sandstone (or quartzite) made essentially of quartz is expected to be more durable. The weatherability of these siliceous rocks is strongly influenced by the nature of minor constituents like feldspar.

During its use as a building stone, other components are introduced into the rock which can accelerate its weathering. For example, minor amounts of lime mortar and plaster may be vulnerable to acid attack. Moreover, many buildings show discoloration of stone facings due to oxidation of iron bars attached to the structural framework (Gauri, 1981; Jain et al., 1988).

1.1 Objectives

Keeping these factors in mind, the objectives of the present thesis project can be listed as follows :

1. To study the ancient monuments at Kusum Van Sarovar Complex in detail, with special emphasis on the type of construction material adopted in ancient time.
2. To collect representative samples of building stones from the site to investigate the possibility of varying degree of weatherability.
3. To trace and locate the original quarry from which these building stones were obtained (confirmed to be from Bansipaharpur, Dhauri Quarry, Rajasthan) and to collect representative samples for laboratory study.
4. To study the mineralogy of the samples collected from the field using standard techniques, such as petrography and

X-ray diffraction.

5. To carry out standard physical tests to determine water absorption, apparent specific gravity, and apparent porosity.
6. To utilize the laboratory data to build up a weathering model following the earlier work of Sharma (1991) on Khondalite used in Konark Sun Temple.
7. To synthesize the results for a comparative study of the decay of two important silicate rich building materials namely, sandstone and Khondalite.

CHAPTER 2

LITERATURE REVIEW

2.1 Geological Setting of the Area

The sandstone - shale sequence of Bansipaharpur area stretches for a length of 20 - 25 km., covering part of eastern Rajasthan near Bharatpur - Piplwis. Pascoe (1965) has placed this sequence in geologic time period of Lower Delhi Super Group.

Development of high land facies along the eastern margin and a deep water facies at the centre are some notable features of the Aravallis. The Berach Granite marked the terminal phase of Archaen Cratonization event. The contacts of the Delhi rock with the Pre - Delhi rocks are tectonic. The Delhi rocks are found to have crystallized first under regional metamorphism leading to an extensive development of amphibolite facies assemblages, except in the Lalsot - Bayana region in the NE where green schist facies assemblages developed. The age span of the Aravalli and the Delhi rocks is not yet firmly established. For the Aravalli rocks, the upper limit is fixed by the 1900 ± 80 Ma age of the Darwal granite (Chowdhary et al., 1984) emplaced syntinetically with the first folding of the Aravalli rocks. The assumption that the Aravalli sedimentation post date 2500 Ma is based on the possible ~ 2500 Ma age of the pre - Aravalli Berach granite.

The Delhi supergroup, presuming a Delhi - Aravalli unconformity, must have formed later than 1950 Ma Darwal granites. However, as in the case of Aravalli supergroup, the lower limit of the Delhi rocks is yet to be defined. According to more recent

field data, the age of Ajitgarh granite (K50 Ma) which shows distinctly intrusive relationship and syntkinematic characters (Roy and Das, 1985) may be taken as the date of closing of the Delhi orogeny.

During Archaean time, the landscape of pre - Aravalli supergroup was dominated by high land areas. Granite and related rocks were the preponderant constituents of these high lands. These rocks were sources of arenitic detritus in the adjacent syncline whose depositional environment varied. A regional complex of continental and shallow marine environments existed.

2.2 Sandstone as a Sedimentary Rock

Sandstone is a sedimentary rock having more than 70% sand-size particles and 30 or less than 30% void spaces, filled by matrix/cement. On the basis of matrix content, sandstone is grouped into two categories, (1) with silica rich matrix, (2) with carbonate rich matrix. Quartz is one of the most common and least weatherable minerals in sandstone. Potash-feldspar is another major mineral. The pink or red colouration of sandstone is due to presence of iron oxides like haematite, goethite etc. However, these iron oxides may be forming only a very small part of the whole rock. A feldspar rich sandstone grades into Arkose while with a higher proportion of clay size particle it is classified as Claywacke. Most sandstone are derived by the weathering of granitic rocks. After arenaceous sediments are carried to the basin of deposition, they undergo diagenetic effects before consolidation into sandstone rock. The porosity reduces through

compaction and cementation. Unstable detritals are lost and stable authigenic precipitates are added. The end product of long continued deep burial of a quartz arenite will be completely cemented quartzite.

The mechanism for the formation of spotted appearance of sandstone can be explained in the following manner. When the interstitial fluid came into contact with iron bearing silicate grains e.g. biotite, augite etc. in Precambrian time, the atmosphere then probably contained more CO_2 than at present, making surface water more acidic. It helped to alter the silicate minerals. Hydraulic gradient facilitated the local removal of soluble products to prevent saturation. The released iron can remain in solution as Fe^{+2} ions or be precipitated as ferric oxide depending on the oxidation potential (Eh) and acidity - alkalinity (pH) of the water (Fig. 2.1). The ferrous iron, Fe^{2+} , can remain in solution if the solution stays reducing and slightly acidic and not mix with the other ions that form insoluble compounds. However, when this delicate balance of conditions is broken, precipitation occurs e.g. as solution becomes slightly alkaline, the precipitation of ferric oxide may occur. During the later history of sediment, the changes might have occurred in the Eh - pH of the interstitial water many times. The differences in iron content in spotted sandstone may reflect these post depositional redistribution of iron. The spots show selective leaching and precipitation of iron minerals.

The degree of resistance that sandstone offers to weathering depends on its mineralogical composition, texture, porosity, type and amount of cement, and the presence of any

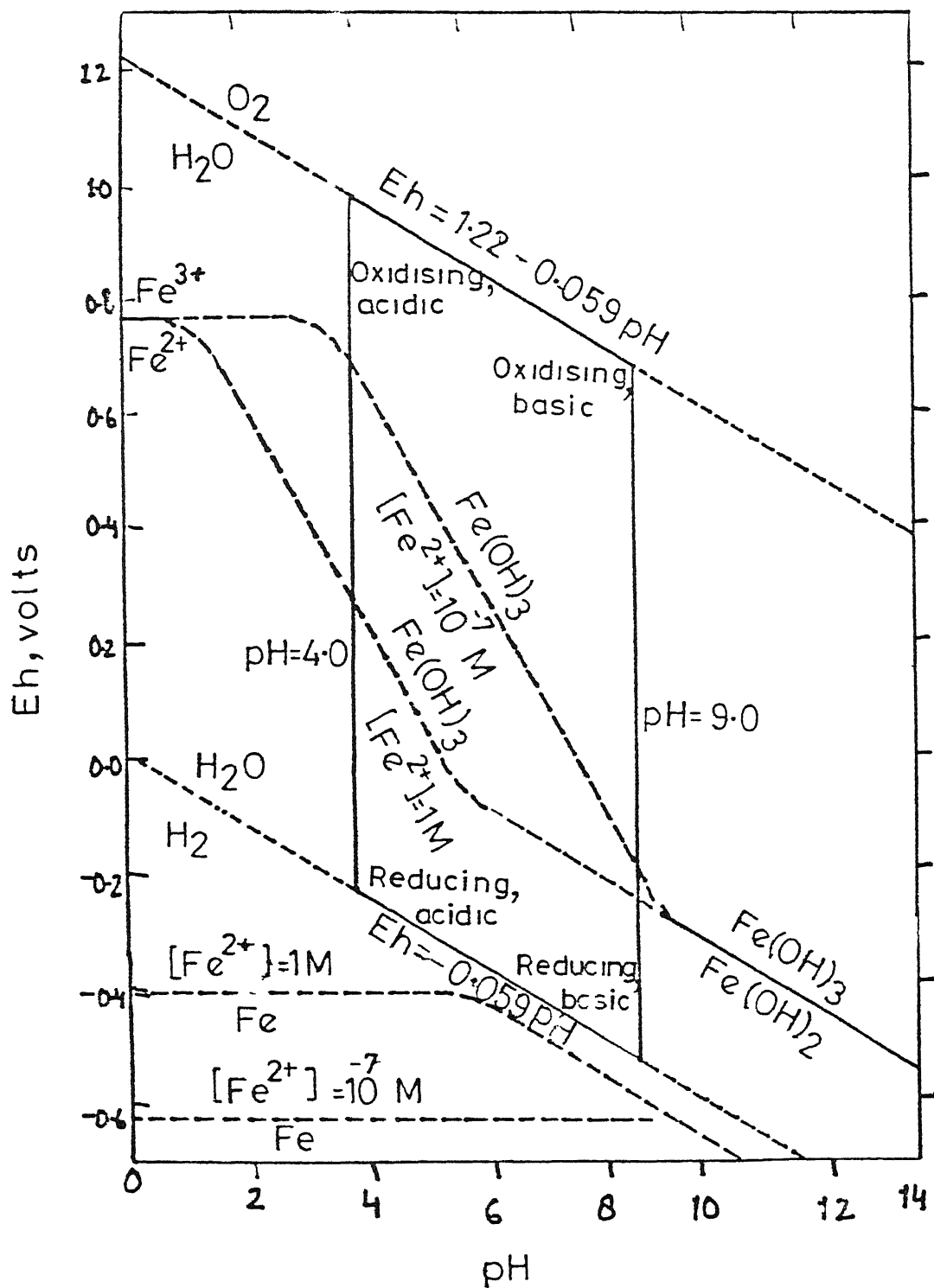


Fig. 2.1 Eh-pH diagram for the simple ions and hydroxides of iron at 25°C (Krauskopf, 1982).

planes of weakness.

The process of weathering represents an adjustment of the minerals, of which a rock is composed, to the conditions prevailing at the Earth's surface and so the type of weathering varies from one climatic region to another.

Sandstone decomposes with time as a result of chemical, biological and mechanical processes acting in combination.

2.2 Factors affecting the Durability of Stonework and Remedial Measures

Well exposed surfaces of stone transmit moisture from rain and fog and may sometimes permit deep penetration. Ground moisture is derived from splashing rain as well as ground water. Both contain more ions than rain water. Pao et al. (1981) found that the strength of intact rock decreases with an increase in moisture content.

Water is the most important agent of weathering. It gains access to the pores of stone by gravity, osmotic, capillary and siphon action. Because the common rocks are hydrophylic, water can penetrate extremely small openings. Water hydrates, hydrolyzes and dissolves the mineral components of rocks. For example, the hydrolysis reaction of orthoclase (K-feldspar) forms kaolinite.

Stone can be damaged by the repeated action of wetting and the expansive force of water can represent a disruptive influence, particularly in the pores of a stone of low tensile strength.

Water inhibiting minerals may swell within stone and

thereby facilitate its disintegration. Swelling may also take place due to inter layer hydration of minerals like some iron hydroxides or anhydrite.

Decomposition of stonework by the action of organisms or by the products of organic processes is often regarded as minor compared with the direct chemical effects. However, the aggressiveness of water in chemical reactions involving minerals can be increased by the presence of organically produced constituents such as O_2 , organic acids, and CO_2 . Bacteriological action can promote rock disintegration through utilization of chemical constituents of minerals for organic processes and can introduce metabolic products that have a catalytic effect on further physico - chemical weathering.

Bacterial action on stonework and/or mortar involves the absorption of energy from solar radiation to constituents of the rock. Weathering rates can be increased by bacteria within micro fractures attacking silicates, carbonates, and oxides. The activity is not confined only to the surface of exposed rock but deeper.

In order to repair or restore stone work, it is best if the same stone as the original is used. There are two principal means by which stone can be preserved. One involves the formation of an outer stabilized zone around the stone; the other alters the chemical composition of the stone. Vinyl monomers, epoxies and alkoxysilanes are three popular systems which offer a promising approach to stone preservation via polymerization of monomers. Silanes comprise both organic and inorganic hydrid molecules of very small size similar to that of a water molecule. When the

silane is spread on the surface of a rock. one end of each molecule bonds itself chemically to the silicates present in the rock structure adjacent to any pore space while the other end forms a permanent hydrophobic layer which repels water but still allows the rock to allow the passage of moisture from inside to come upto surface. By penetrating to a depth of several centimeters, use of the monomer overcomess the problem of contour sealing. The cost of such treatment is very high.

Only with the effective cooperation of designers, geologists and geotechnicians it is possible to determine factors of deformation of historical structures. The lack of cooperation and insufficient identification of factors of deformation of historical structures may result not only in a low efficiency of applied remedial measures, but in some cases may cause further damage.

CHAPTER 3

METHOD OF WORK

This thesis project essentially involved field work and laboratory tests.

3.1 Field Investigation and Sample Collection

For sample collection, a field trip was made to the site of the monument as well as to the quarry, from where the building stone was brought for construction.

The site, known as Kusum Sarovar Complex, is located at Govardhan, 21 km. West of Mathura (U.P.). Representative samples were collected from various structures which appeared to be in different stages of weathering.

After that, a field - trip was made to Bansipaharpur area, 60 km. NE of Bharatpur (Rajasthan). According to available information, sandstone for construction of Kusum Sarovar Complex was taken from Dhauri quarry more than 200 years back. This quarry is still operative. In an exposed profile of the quarry, the soil cover of varying thickness is underlain by a 1.2 m thick zone of friable red - brown shale. A red sandstone extends to 3 m below this shale followed by a buff coloured sandstone upto a maximum depth of 12 m. Only this light coloured sandstone is commercially utilized as a building material. For quarrying purpose, the overburden consisting of soil, shale and red sandstone is removed by blasting.

Samples of shale, partially weathered sandstone exposed in outcrops and fresh sandstone from the lower level of the quarry were collected for laboratory studies.

3.2 Laboratory Work

The laboratory work consisted of two parts :

(i) measurement of some index physical properties like water absorption, specific gravity and porosity.

(ii) thin section study of the samples along with XRD study.

3.2.1 Water Absorption

The quick absorption method (Hamrol, 1961) was used to find the saturation moisture content of a rock sample. A sample was oven dried at $100 - 105^{\circ}\text{C}$ for an hour and weighted (w_1). It was then kept submerged in distilled water, at room temperature, for $1\frac{1}{2}$ hour. After this period, excess water was wiped off and the sample was air dried for 5 - 10 minutes. Then the weight of the sample (w_2) was determined by a digital chemical balance.

Water Absorption was calculated as :

$$\% \text{ Absorption} = \frac{w_2 - w_1}{w} \times 100$$

3.2.2 Apparent Specific Gravity and Porosity

This method was adopted from IS : 1124 - 1974. The sample was weighed when dry (w_1). A known volume of water was taken in a measuring cylinder (V_1). The sample was submerged in the measuring cylinder the level to which the water rose was noted (V_2).

Apparent Specific Gravity was calculated as :

$$\text{App. Specific Gravity} = \frac{w_1}{V_2 - V_1}$$

The apparent specific gravity and water absorption values were used to calculate Apparent Porosity of the rock sample using the formula given in the code.

Apparent Porosity = Water Absorption \times Apparent Specific Gravity.

3.2.3 X-Ray Diffraction

X - ray diffractograms were obtained from bulk powder and oriented slides (prepared by depositing a suspension on glass plate).

The oriented slides are useful in enhancing the low angle basal peaks of flaky minerals like clays. An IsoDebyeflex 100 + model Rock Siefert (USA) diffractometer was used with copper target and nickel filter.

3.2.4 Thin Section Study

Hand specimen and polished surface were observed under a Bausch and Lomb (USA) Binocular microscope under magnification ranging from 14 x to 60 x.

Thin sections were studied under a Leitz Laborlux 11 Pol S (Leitz Wetzlar Germany 553 428) polarising microscope with varying magnifications. The analyser plate was used to obtain characteristic interference colours.

RESULTS AND DISCUSSION

4.1 Description of Site.

The two types of field sites have been described below :

- (i) monuments at Kusum Sarovar.
- (ii) source area of sandstone at Pansipaharpur.

4.1.1 Kusum Sarovar Complex.

The area selected for the present study is known as Kusum Sarovar, located at Govardhan, 21 km. West of Mathura. It is a beautiful complex covering 225 m x 290 m area with a large pond (Sarovar) in the front and several domed buildings (Chhatries) at the back [Fig. 4.1]. The pond is believed to be ancient. There are legends connecting it with the time of Lord Krishna. The chhatries were built by Raja Jawahar Singh of Bharatpur in the 18th Century (1763 - 1765 A.D.) in memory of his father Raja Surajmal and Surajmal's three queens.

The prominent landform around Kusum Sarovar is 'Giriraj Parwat' running further SSW of it and rising upto height of 120 - 200 m at places. Just before Kusum Sarovar, it comes to the ground level. The Sarovar Complex is built on hard rock. Yamuna river is about 22 km. away, East of Govardhan towards Mathura. The site is surrounded by agricultural land with no big industry in close proximity, except a few brick kilns. The Mathura Refinery is at about a distance of approximately 30 km.

These domed buildings which infact are Chhatries (sepulchral tombs) of the Royal family of Bharatpur, Raja

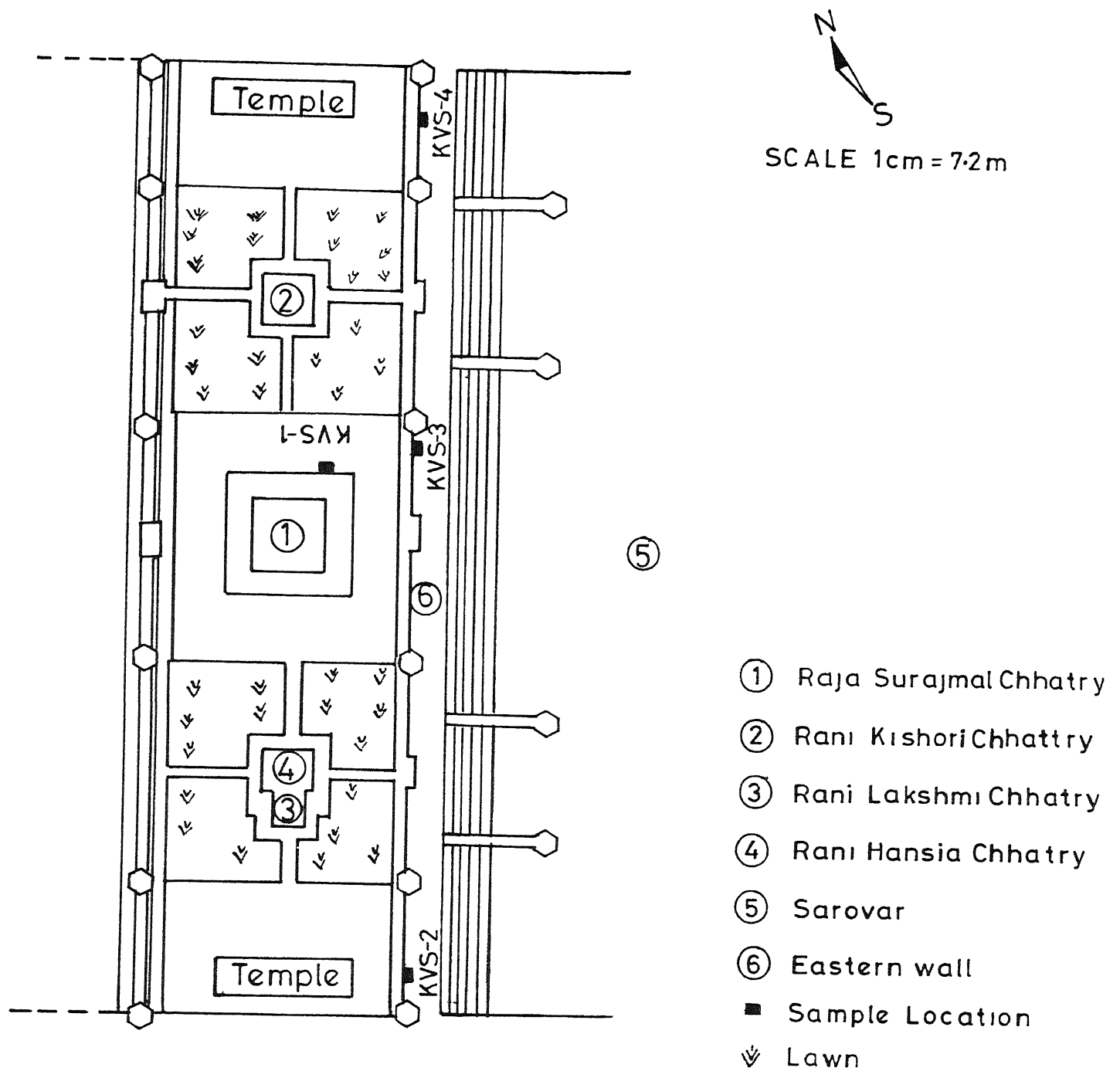


Fig.4-1 Location map of Kusum Sarovar complex, Mathura.

Surameli and his three queens, Rani Kishori, Rani Lalohmi and Rani Honsia, are placed over a high platform of sandstone. The central Chhatra is biggest of all, i. e. of Rani Surameli, flanked by three small Chhatras of his three queens. Besides these main buildings, there are smaller canopies and balconies all around.

The main construction materials used are :

- (i) light buff coloured sandstone.
- (ii) lime rich mortar and plaster, used to bind the sandstone slabs.
- (iii) bricks of 17 cm x 10 cm x 6 cm dimension, known as 'Lathori' bricks.
- (iv) some glue like unidentified material used for jointing sandstone pillars and domed roof pieces etc.

The lime mortar and plaster were identified to be rich in carbonate because of strong effervescence with dilute acid. It was later confirmed to contain calcite by XRD [Fig. 4.2]. The whole Kusum Sarovar Complex can be divided into two parts : One is at the ground level, another at the high platform where Chhatras are built. At the ground level, there is uniform deterioration in the stone blocks, rock pillars and excavated rock faces. Closer examination revealed that the rock deterioration consisted of bulging, peeling of paints, loss of surface layer [Figs. 4.3 and 4.4], cracking of pillars and formation of salt layers (efflorescence). Rock decay is relatively less severe at the upper portion, the main evidence being cracking of pillars and peeling of plaster. This cracking of pillars may be attributed to volume expansion during the rusting of iron dowels,

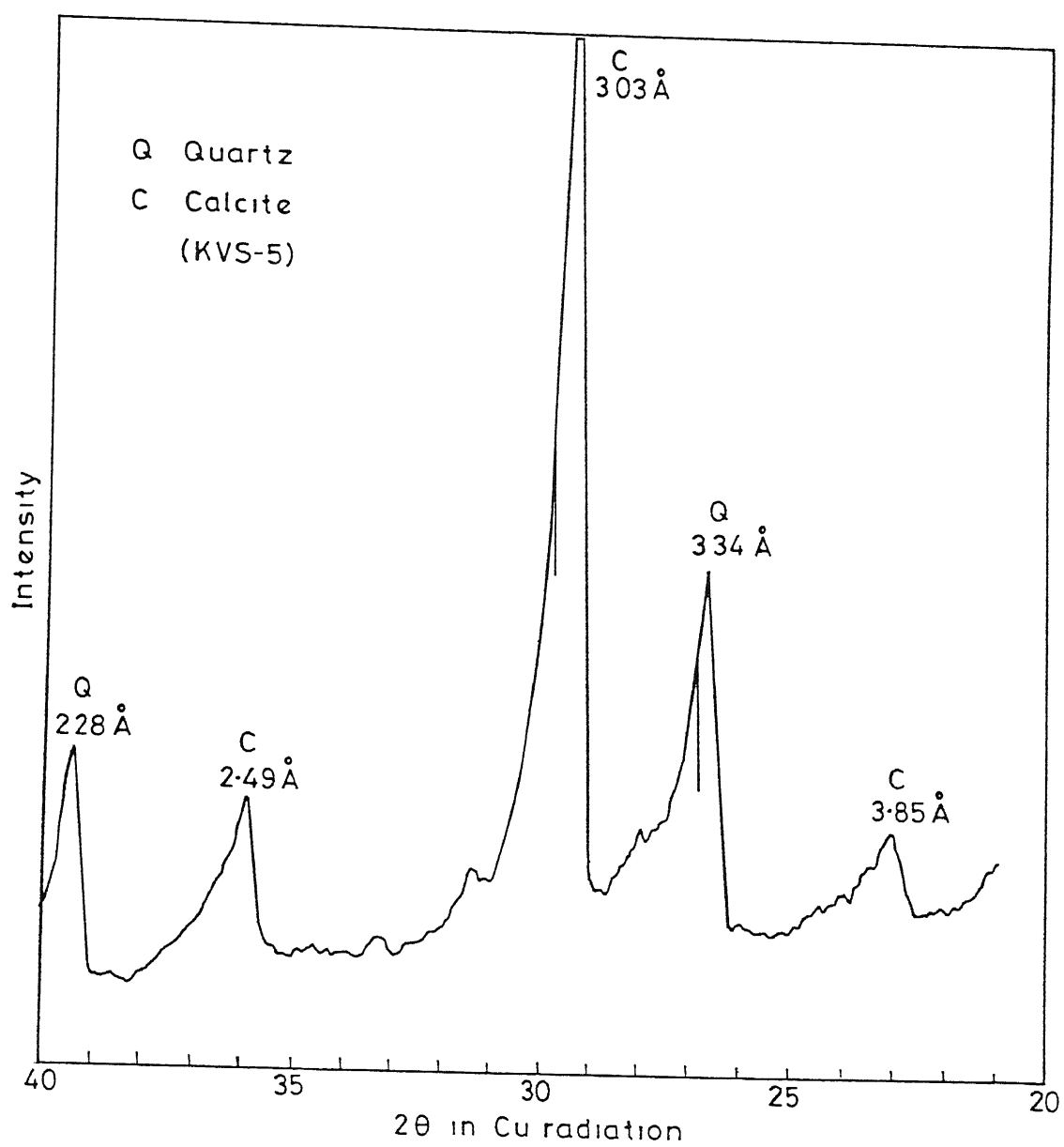


Fig 42 XRD of Mortar



Fig. 4.3 Photograph of Eastern Wall of Kusum Sarovar Complex showing signs of decay.



Fig. 4.4 Photograph of brick wall near Kusum Sarovar, showing salt crust, mortar and weathered stone slab.

used to clamp the stone blocks. Efforts are being made to replace these iron fittings with high quality steel rods and pipes.

The roof of the central chhatry has been invaded by the root of a big tree. Although, the tree has been subsequently cut off, the root is still a channel for water seepage. Another interesting feature in the central chhatry is a very thin layer of plaster on the sandstone floor which has been polished to a marble finish. The plaster reacts vigorously with dil HCl and hence is concluded to be of carbonate composition.

Lime plaster used on various walls is showing signs of cracking and has fallen off in large chunks.

During restoration work, the plaster has been secured to the wall by injecting a putty of fevicol and lime at the undersurface wherever the gap within the wall was large. Fine cracks had been filled with a mixture of lime and marble powder and a final coat of fine lime has been given over it.

The efflorescence on stone surface consists of water soluble salts. X-ray patterns of this material shows a mixture of quartz and sodium sulphate (Na_2SO_4) [Fig. 4.5].

Various samples collected from the site have been described in Table 4.1.

4.1.2 Bansipaharpur Quarry.

Personal communication from officials of Archaeological Survey of India and local villagers indicated that the sandstone for building the Kusum Sarovar Complex was brought from Dhauri Quarry at Bansipaharpur, Rajasthan. It is also learnt that the same royal family who constructed the Kusum Sarovar Complex, used

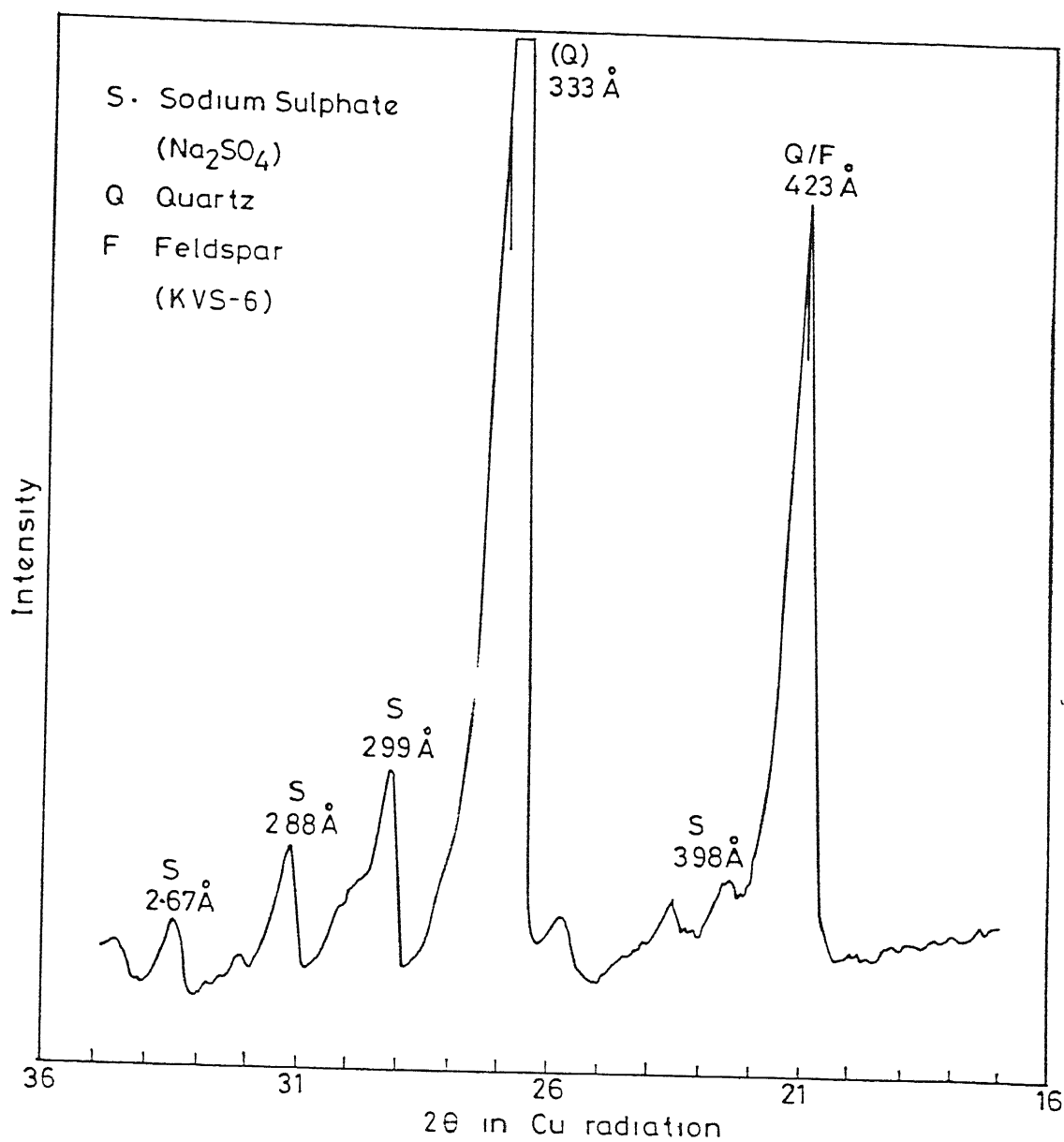


Fig.45 XRD of Salt Crust

Table 4.1 Description of samples collected from Kusum
Sarovar Complex.

SAMPLE NO	DESCRIPTION (FIG.4.1)
KVS- 1	From the NE side of the pedestal of Raja Surajmal Chhattri/ Pale cream coloured sandstone. Relatively Fresh.
KVS - 2	From the Southern end of the Eastern wall. Sandstone of light red-brown colour showing limited weathering.
KVS - 3	Sandstone taken from the middle of the Eastern wall showing high degree of weathering. Layers peeling off. Efflorescence is present.
KVS - 4	Taken from the Northern end of Eastern wall. Highly weathered sandstone of pale red colour. Efflorescence and peeling of layers are common.
KVS - 5	Mortar and plaster
KVS - 6	Efflorescent salt crust
KVS - 7	Brick used in construction.

Bansipaharpur sandstone for building the palace of Deeg. 15 km. further West of Govardhan.

Bansipaharpur is located approximately 60 km NE of Bharatpur. As mentioned in Chapter 3, quarrying is still active throughout this area. Sandstone of different colours occur along a hill in a NE-SW direction. Rocks at the Dhauri quarry have low dips around 4° towards SE. The samples collected from the quarry have been described in Table 4.2.

4.2 Mineralogy of Sandstone.

Observations of samples in hand specimen, under binocular and petrological microscope and results of X-ray studies are summarized below.

The fresh sandstone is light coloured with unevenly distributed brownish spots in a few samples. In thin section, the main minerals recognized were quartz, K-feldspar and iron oxide [Fig.4.6]. Quartz grains are anhedral to subhedral and frequently showed undulose extinction suggesting deformation during crystallization. While the detrital fraction is predominantly quartz, minor amounts of K-feldspar and iron oxides are present in all samples. K-feldspar grains commonly showed twinning and frequent cloudiness due to weathering to clay minerals [Fig. 4.7]. Cement material between quartz grain is apparently siliceous because of its lack of reaction with dilute acid. Dark grains of iron oxides filled pore spaces and fractures within quartz grains.

The overall mineralogy of the brown spots within pale sandstone appears to be the same although the proportion of iron oxide minerals was higher and the grain size within the spot was

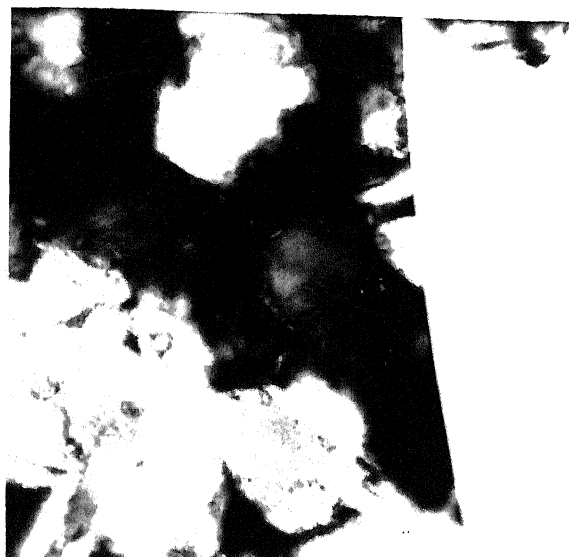


Fig. 4.6 Microphotograph under X-nicol
oxide and twinned feldspar gr
(BP-2) 100 X.

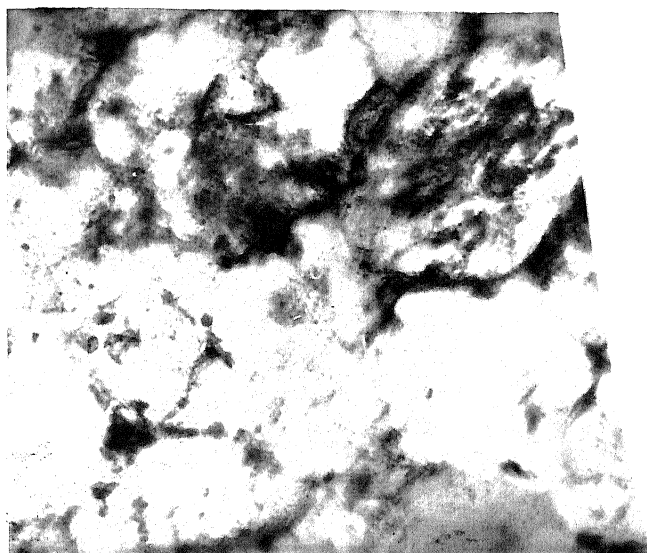


Fig. 4.7 Microphotograph in plane polarised light
weathered feldspar grains in sandstone (1

Table 4.2 Description of samples collected from Bansipaharpur area.

SAMPLE NO	DESCRIPTION
BP - 1	Partly weathered pale cream coloured sandstone exposed at the surface of Dhauri quarry.
BP - 2	Very light buff coloured sandstone, quarried from the lower depth of Dhauri quarry. There are dark coloured, unevenly distributed spots in the sandstone. Relatively fresh.
BP -3	Red - brown shale from the top layer exposed at quarry.

relatively finer. This texture may have resulted due to the leaching action of interstitial water and reprecipitation of oxidized iron under changing Eh-pH conditions.

Fig. 4.8 and 4.9 are typical X-ray diffractograms of partially weathered sandstone from the quarry and Kusum Sarovar Complex. Table 4.2 to 4.8 list all the X-ray peaks observed in various samples. Most of the minerals observed in thin section e.g. quartz, K-feldspar and iron oxide were confirmed from their X-ray peaks. The clay alteration product of feldspar was indentified to be kaolinite (7.15 \AA , 3.75 \AA X-ray peaks). The X-ray diffractograms showed basal peaks at 9.9 \AA which is for illite and at 9.02 \AA which may be due to pyrophyllite. While illite is commonly a minor constituent of sandstone, the presence of pyrophyllite requires some discussion. It is probably a minor constituent of the Bansipaharpur sandstone because most higher angle peaks have been submerged by the large proportion of quartz.

There are two distinct possibilities regarding the origin of this mineral in the sandstone. One is the weathering of primary K-feldspar to pyrophyllite under low temperature conditions. The relevant reactions are given in the appendix 1 and the thermodynamic stability diagram, based on data available from Drever (1988), is shown in Fig. 4.10. It is obvious that compared with kaolinite, pyrophyllite is a stable weathering product under higher silica activity and lower K^+/H^+ activity ratios. The second possibility for the origin of pyrophyllite is the reaction :



It takes place during low grade matamorphism. The physicochemical

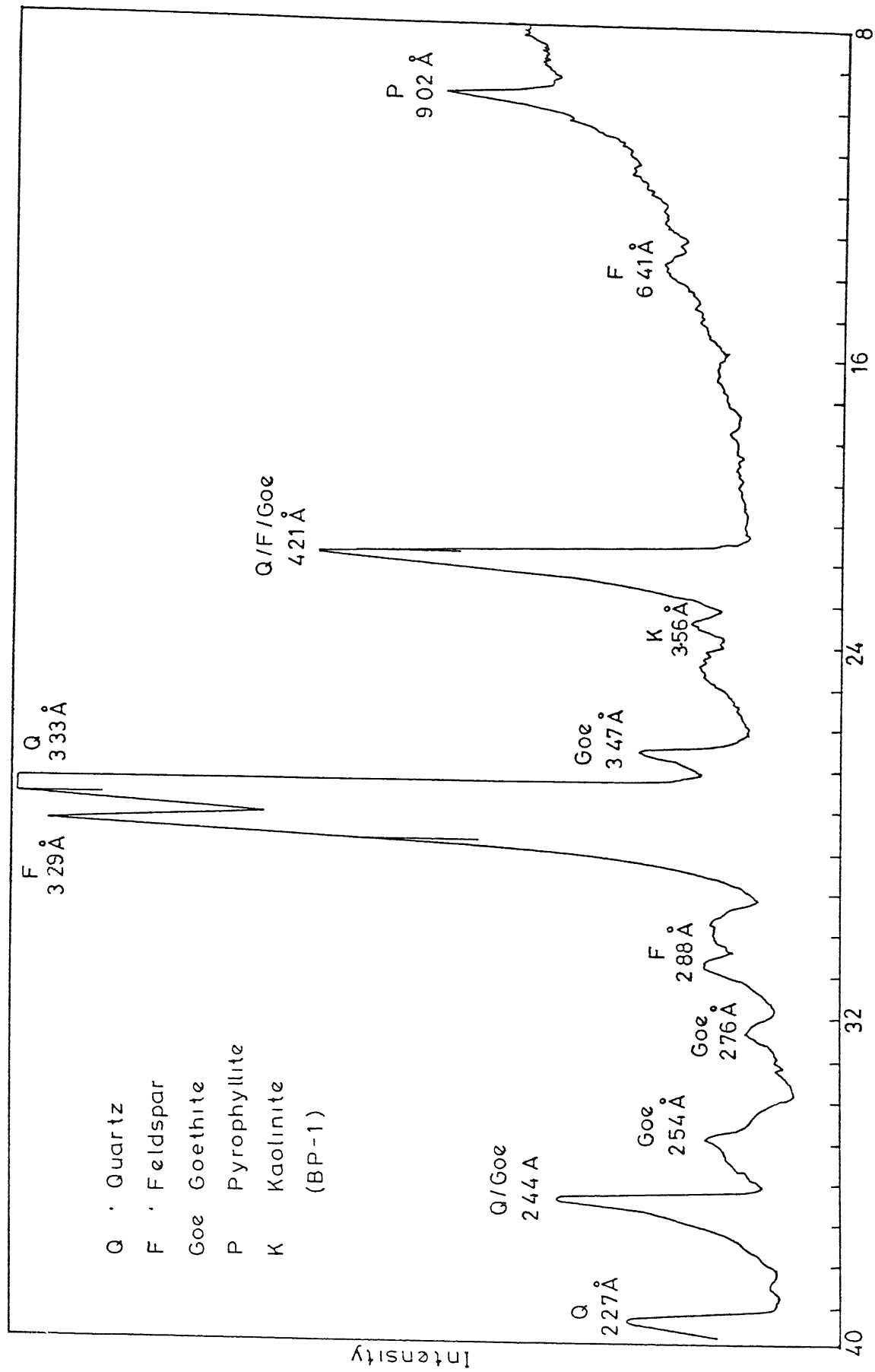


Fig 4.8 XRD of Quarry Sandstone

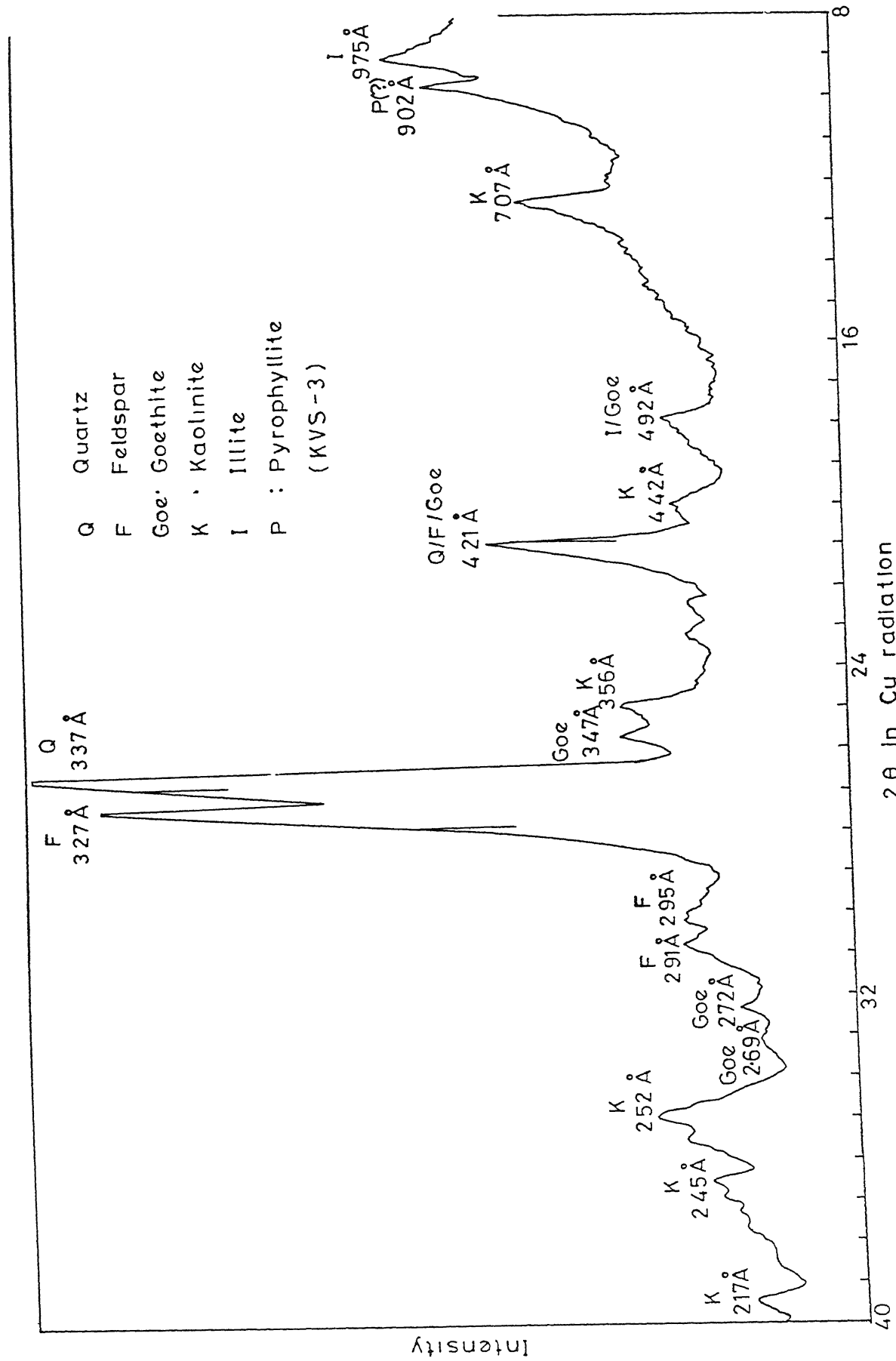


Fig 4.9 XRD of Weathered Sandstone of site

Table 4.3 Identification of X-Ray Peaks for BP-1

2θ Cu - radiation	d (\AA)	MINERAL
9.80	9.02	P (?)
13.8	6.41	F
21.1	4.21	Q/F/Goe
22.6	3.56	K
25.7	3.47	Goe
26.8	3.34	Q
27.5	3.29	F
31.0	2.28	F
32.6	2.76	Goe
35.2	2.54	Goe
36.8	2.44	Q/Goe
39.6	2.27	Q
40.4	2.23	Q
42.0	2.15	F
42.7	2.12	Q

P = Pyrophyllite; Q = Quartz; F = Feldspar; K = Kaolinite;

Goe = Goethite

Table 4.4 Identification of X-Ray Peaks for BP-2

2θ Cu - radiation	d (\AA)	MINERAL
8.9	9.75	I
12.3	7.20	K
13.6	6.41	F
20.9	4.24	Q/F/Goe
25.7	3.42	Goe
26.7	3.33	Q
27.5	3.25	F
36.7	2.45	Q/Goe
39.6	2.27	Q
42.7	2.12	Q

I = Illite; K = Kaolinite; F = Feldspar; Q = Quartz;

Goe = Goethite.

Table 4.5 Identification of X-Ray Peaks for KVS-1

^{2θ} Cu - radiation	d (Å ⁰)	MINERAL
13.9	6.36	F
21.0	4.21	Q/F/Goe
25.6	3.47	Goe
26.6	3.35	Q
27.4	3.25	F
29.5	3.02	P
32.4	2.76	Goe
35.4	2.53	K
36.6	2.45	K
39.5	2.28	K
40.4	2.23	Q
41.9	2.15	F
42.6	2.12	Q
45.8	1.98	Q
47.7	1.90	Q
48.7	1.87	Q
50.2	1.81	Q

F = Feldspar; Q = Quartz; Goe = Goethite; P = Pyrophyllite;

K = Kaolinite.

Table 4.6 Identification of X-Ray Pattern for K/S-2

2θ Cu - radiation	d (\AA^0)	MINERAL
13.7	6.45	F
20.8	4.26	Q/F/Goe
25.6	3.47	Goe
26.6	3.35	Q
27.5	3.24	F
30.8	2.89	F
32.4	2.76	Goe
35.1	2.55	K
36.3	2.47	K/Q
39.5	2.28	K
40.4	2.29	Q
41.8	2.16	F
42.5	2.12	Q
45.9	1.97	Q
50.3	1.81	Q

F = Feldspar; Q = Quartz; Goe = Goethite; K = Kaolinite.

Table 4.7 Identification of X-Ray Peaks for KVS-3

2θ Cu - radiation	d (\AA^0)	MINERAL
9.1	9.75	I
9.6	9.02	P(?)
12.6	7.07	K
18.0	4.92	I/Goe
20.1	4.42	K
21.1	4.21	Q/F/Goe
25.1	3.56	K
25.8	3.47	Goe
26.4	3.37	Q
27.7	3.27	F
30.3	2.95	F
30.9	2.91	F
32.4	2.72	Goe
33.2	2.69	Goe
35.1	2.52	K
36.7	2.45	K
39.6	2.17	K

I = Illite; P = Pyrophyllite; K = Kaolinite; Goe = Goethite;

Q = Quartz.

Table 4.8 Identification of X-Ray Peaks for KVS-4

2θ Cu - radiation	d (Å)	MINERAL
9.00	9.82	I
9.8	9.01	P(?)
18.0	4.92	I/Goe
20.1	4.42	K
21.0	4.23	Q/F/Goe
22.7	3.56	K
25.7	3.47	Goe
26.7	3.33	Q
28.0	3.28	F
29.6	3.01	P
31.1	2.89	F
36.7	2.45	Q/Goe
39.6	2.297	K
40.4	2.17	F
42.7	2.12	Q

I = Illite; P = Pyrophyllite; Goe = Goethite; K = Kaolinite;

Q = Quartz; F = Feldspar.

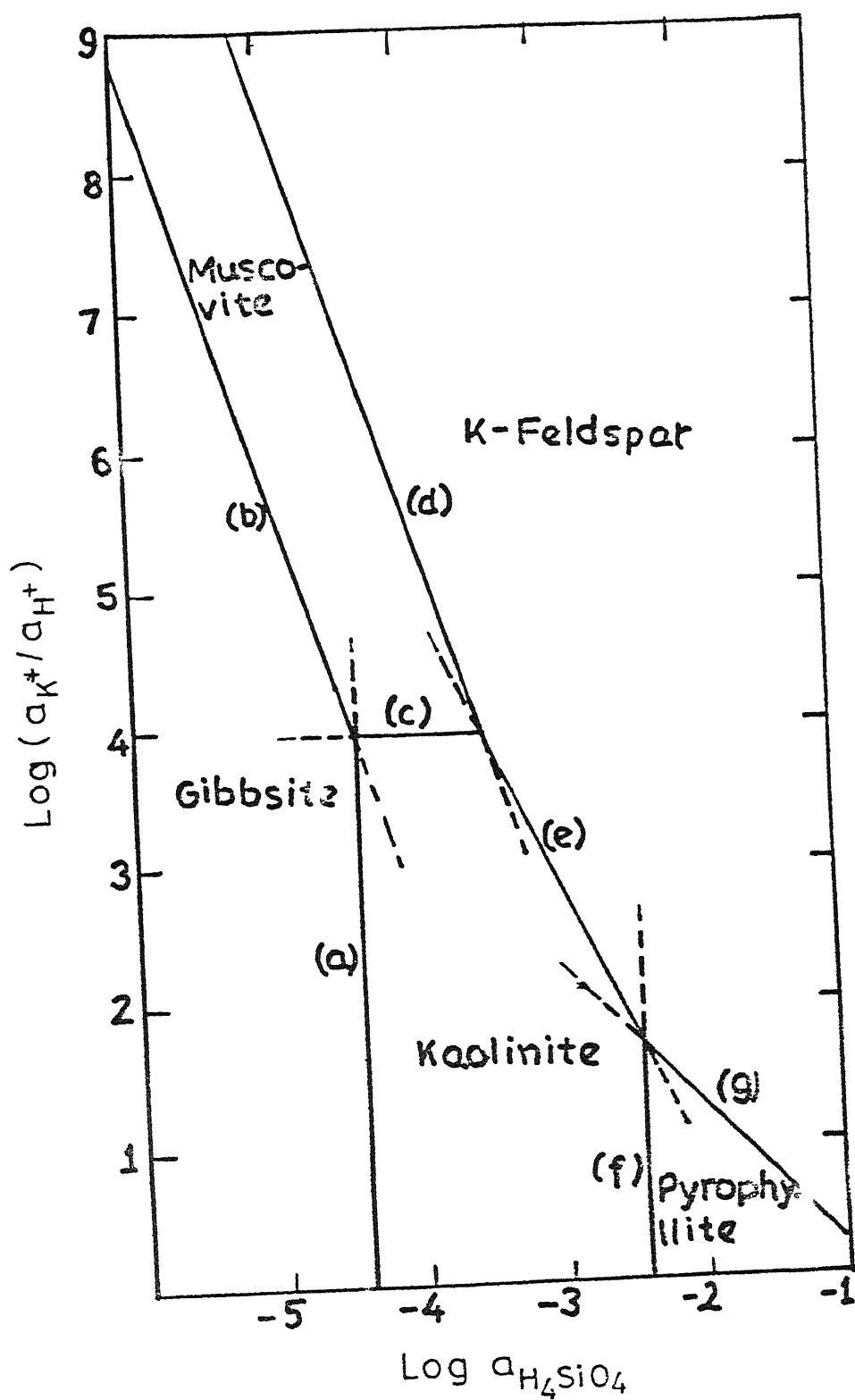


Fig. 4.10 Thermodynamic stability diagram of minerals in the system $\text{K}_2\text{O} - \text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{H}_2\text{O}$ (Drever, 1988).

conditions for metamorphic origin of pyrophyllite [Fig. 4. 11] has been quoted as temperature = $240 - 260^{\circ}$ C, Pressure = 1-2 kbar, water activity of 0. 6 to 0.8 (Bailey, 1988).

As X-ray patterns of relatively fresh sandstone does not have pyrophyllite peak and pyrophyllite is present in a few weathered samples, pyrophyllite in these rocks is considered to be a minor product of weathering of feldspar. The main weathering reaction in the sandstone appears to be kaolinisation of K-feldspar.

From mineralogy and texture, the Bansipaharpur sandstone can be considered to contain mainly quartz and K-feldspar before weathering. Therefore, the two mineral model of Lumb (1962) for decomposition of granite can be adopted in this case. A weathering model was developed following the earlier work of Sharma (1991) for weathering of khondalite (Appendix II) and a computer program was written in "C" language on HP - 9000 system to estimate weathering index (X_d) and apparent porosity (n) (Appendix III).

Some physical properties like Apparent Specific Gravity, Water Absorption and Apparent Porosity of sandstone samples, measured in laboratory are given in Table 4.9. It is obvious from these values that as the rock becomes more weathered, the apparent specific gravity decreased whereas the water absorption and apparent porosity values increased. The laboratory measured apparent porosity values ranged from 7.17 % to 8.83 % for relatively fresh to weathered sandstone samples.

The decomposition of sandstone can be represented by alteration of feldspar to kaolinite according to following

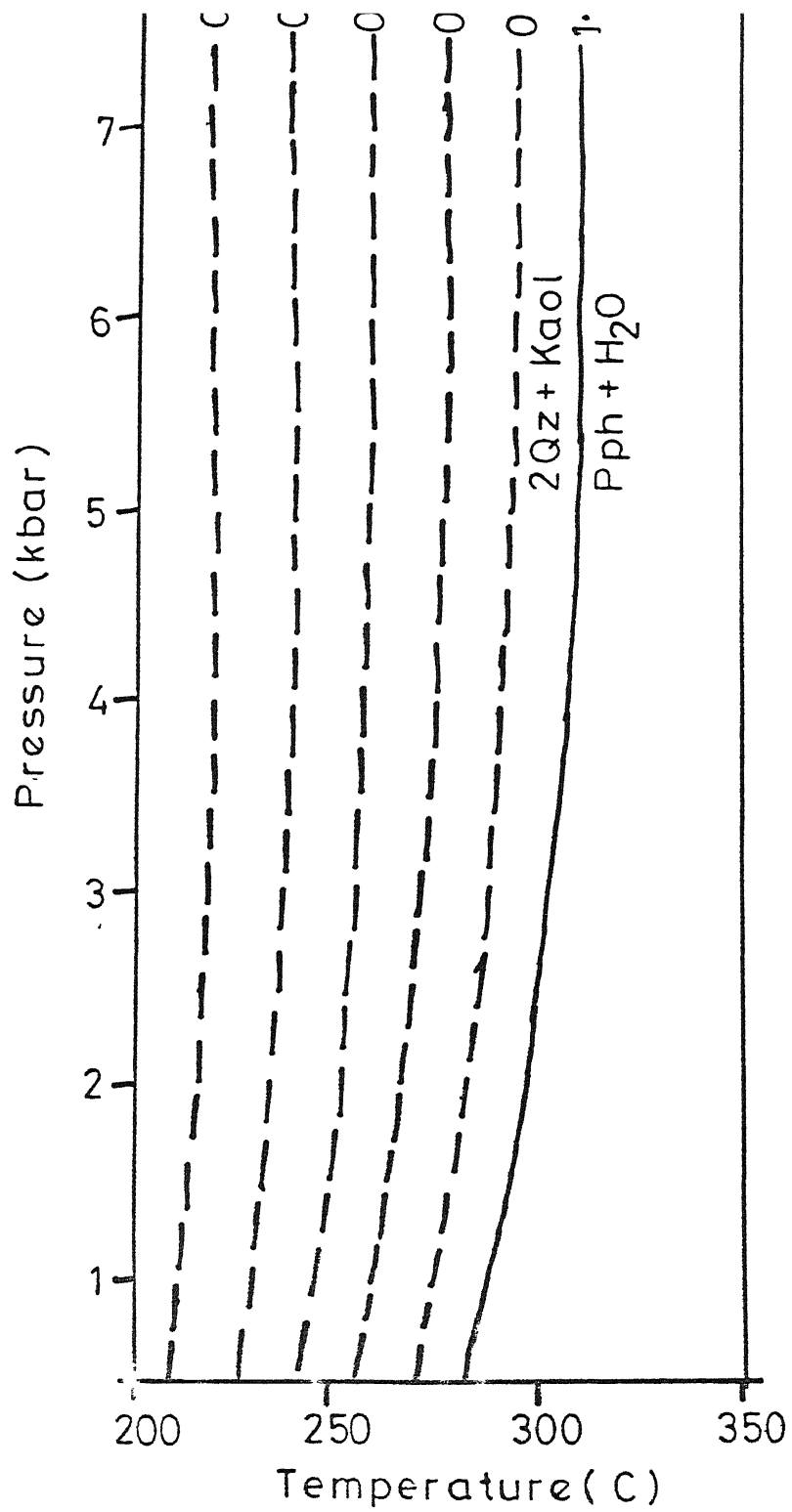
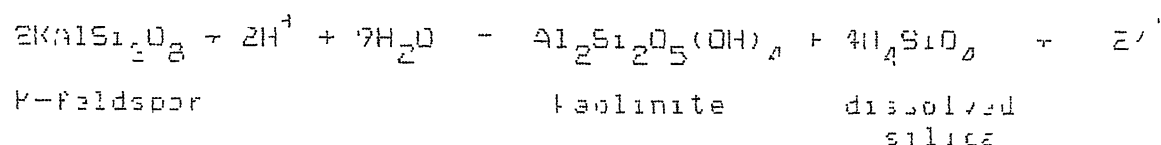


Fig. 4.11 Phase diagram for Pyrophyllite - Kaolinite equilibrium as a function of activity of H_2O (Evans and Guggenheim, 1988).

Table 4.9 Index Physical Properties of Fresh and Weathered
Sandstone Samples

SAMPLE	WATER ABSORPTION (%)	APPARENT SPECIFIC GRAVITY	APPARENT POROSITY (%)
<u>FROM MONUMENT</u>			
KVS-1 (Kusum Sarovar, least weathered)	2.98	2.66	7.93
KVS-2 (Kusum Sarovar, moderately weathered)	3.07	2.64	8.12
KVS-3 (Kusum Sarovar, more weathered)	3.25	2.56	8.32
KVS-4 (Kusum Sarovar, most prominent weathering)	3.46	2.55	8.83
<u>FROM QUARRY</u>			
BP-2 (Bansipaharpur, relatively fresh sandstone)	2.54	2.82	7.17
BP-1 (Bansipaharpur, weathered sandstone)	3.23	2.62	8.47

reaction



The porosity of the weathered rock can be calculated from the stoichiometry of the reaction. For example

$$\text{Molar volume of the K-feldspar } (\bar{V}_f) = \frac{\text{Molecular weight}}{\text{Specific gravity}} = \frac{278.35}{2.58} = 107.89 \text{ cc}$$

$$\text{Molar volume of the kaolinite } (\bar{V}_k) = \frac{258.17}{2.60} = 99.30 \text{ cc}$$

2 moles of K-feldspar are weathering and forming 1 mole of kaolinite.

$$\text{therefore, \% change in molar volume } (\Delta\bar{V} \%) = \frac{\bar{V}_k - 2 \cdot \bar{V}_f}{2 \cdot \bar{V}_f} \times 100$$

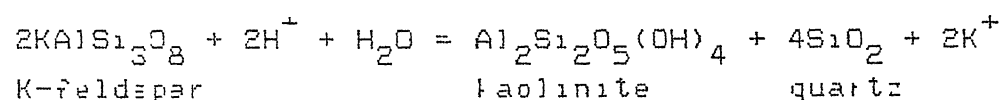
$$= \frac{(99.30 - 2 \times 107.89)}{2 \times 107.89} \times 100$$

$$= \frac{99.30 - 215.78}{215.78} \times 100$$

$$= -53.98 \%$$

Hence, weathering of feldspar to kaolinite results in 53.98 % volume loss.

From a survey of altered wall rocks around ore deposits, Hemley and Jones (1964) suggested that quartz was always present as a weathering product. If we rewrite the weathering reaction with quartz in place of dissolved silica as H_4SiO_4 ,



$$\text{Molar volume of quartz } (\bar{V}_q) = 60.09/2.65 = 22.67 \text{ cc}$$

$$\text{Molar volume of K-feldspar } (\bar{V}_f) = 107.89 \text{ cc}$$

$$\text{Molar volume of kaolinite } (\bar{V}_k) = 99.30 \text{ cc}$$

As 2 moles of K-feldspar weather to give 1 mole of kaolinite and 4 moles of quartz,

$$\begin{aligned}\text{Volume change } (\Delta \bar{V}) &= (\bar{V}_k + 4 \cdot \bar{V}_q) - 2 \cdot \bar{V}_f \\ &= (99.30 + 4 \times 22.67) - (2 \times 107.89) \\ &= 189.98 - 215.78 = 25.8\end{aligned}$$

therefore, the apparent porosity will be $\frac{25.8}{215.78} \times 100 = 11.96 \%$

However, this porosity is higher than the measured value and there is no evidence that quartz in weathered sandstone is a weathering product or a precipitate from solution. It appears to be residual from fresh rock. Therefore, this reaction is not feasible in this case.

These porosity values obviously do not represent the real life situation because the rock is not 100 percent feldspar. Various possibilities are considered below.

(i) The rock has a given quartz to feldspar ratio. From X-ray peak heights of quartz and feldspar in Bansipaharpur sandstone, the quartz to feldspar weight ratio in a relatively fresh sample like EP-2 is estimated to be around 2:1 (Table 4.10). Therefore, the initial volume of a rock with 2.0 gm of quartz and 1.0 gm of feldspar will be $\frac{2.0}{2.65} + \frac{1.0}{2.58} = 0.75 + 0.39 = 1.14$ cc.

If there is 53.98% volume reduction of feldspar due to weathering to kaolinite and if it is assumed that quartz remains unaffected by weathering, the final volume will be

$$\begin{aligned}0.75 \text{ cc quartz} + 0.39 \times \frac{53.98}{100} \text{ cc feldspar} &= 0.96 \text{ cc} \\ \text{App. Porosity} &= \frac{1.14 - 0.96}{1.14} \times 100 = \frac{0.18}{1.14} \times 100 = 15.79 \%\end{aligned}$$

(ii) In the above cases, it was assumed that all of the feldspar present in the fresh sandstone weathers to kaolinite. On

Table 4.10 Correlation of Porosity and Weathering Index for Sandstone Samples

LOCATION	SAMPLE NO.	Q/F	n (%)	X _d
BANSIPAHARPUR	BP-1 (more weathered)	2.48	8.47	0.38
BANSIPAHARPUR	BP-2 (relatively fresh)	1.75	7.17	0.22
PUSUM SAROVAR	KVS-1 (less weathered)	2.04	7.93	0.28
KUSUM SAROVAR	KVS-2 (more weathered)	2.12	8.12	0.30

Q/F = Height ratio of 3.33 Å⁰ peak of quartz to 3.27 Å⁰ peak of feldspar in X-ray diffractograms

n = measured porosity (%)

X_d = calculated Weathering Index, as defined in Appendix III.

the other hand, X-ray diffractograms of weathered sandstone show a mixture of feldspar and kaolinite. It is, therefore, likely that only a part of the feldspar has altered to kaolinite. A series of X-ray diffractograms showed that intensity of 3.27 \AA^0 peak of feldspar is reduced by about 40 % from a relatively fresh rock (e.g. BP-2) to more weathered rock (e.g. BP-1). Therefore, we can assume that the only 40 % of original feldspar weathered to kaolinite ($F_{Fw} = 40.0$).

Initial : 1 gm F + 2 gm Q ($V = 1.14 \text{ cc}$)

Final : 0.4 gm F \longrightarrow $0.4/278.35$ moles of F
 : 2 gm Q + 0.6 gm F + $\frac{0.4}{278.35} \times 258.17 \text{ gm K}$
 : $\frac{2}{2.65} \text{ cc Q} + \frac{0.6}{2.58} \text{ cc F} + \frac{0.37}{2.60} \text{ cc K}$
 = $0.75 \text{ cc} + 0.23 \text{ cc} + 0.14 \text{ cc} = 1.12 \text{ cc}$

therefore, apparent porosity = $\frac{1.14 - 1.12}{1.14} \times 100 = 1.75 \%$

This porosity value is lower than measured porosity value. Therefore, some part of the weathering product (kaolinite) must have been leached away subsequent to formation.

(iii) The proportion of kaolinite leached to give the measured porosity can be estimated from the combination of R_l and F_{Fw} at Q/F ratio (F_Q) = 2.0 : 1 (Table 4.11). For example, the measured porosity of around 8.50 % for the weathered Bansipaharpur sandstone sample (sample BP-1) could have been produced when the original sandstone with Q/F ratio = 2.0 : 1 weathered in such a way that only 40 % of the feldspar decayed to kaolinite ($F_{Fw} = 40.0$) and 80 % of the moles of kaolinite generated are retained in the weathered rock ($R_l = 0.8$).

Initial : 2 gm Q + 1 gm F ($V = 1.423 \text{ cc}$)

Final : 0.4 gm F \longrightarrow $0.4/278.35$ moles = 1.4×10^{-3} moles

Table 4.11 Combination of R_l and F_{Fw} for a sandstone with $n=8.5$
and $F_Q = 2.0 : 1$

R_l	F_{Fw}	X_d
0.10	26	0.19
0.20	28	0.20
0.30	29	0.21
0.40	31	0.23
0.50	33	0.24
0.60	35	0.25
0.70	37	0.28
0.80	40	0.30

R_l = Fraction of moles of kaolinite retained in weathered rock

F_{Fw} = Weight fraction of weathered feldspar

X_d = Calculated Weathering Index, as defined in Appendix II.

$$\begin{aligned}
 & \text{or, moles of kaolinite} = 0.72 \times 10^{-3} \\
 & \text{out of total } 0.72 \times 10^{-3} \text{ moles of kaolinite} \\
 & \text{produced, the fraction of moles of kaolinite} \\
 & \text{retained (for } R_f = 0.8) = 0.72 \times 10^{-3} \times 0.8 \\
 & \quad = 5.76 \times 10^{-4} \\
 & : 2 \text{ gm Q} + 0.6 \text{ gm F} + 5.76 \times 10^{-4} \times 258.17 \text{ gm K} \\
 & = 0.7547 \text{ cc} + 0.2325 \text{ cc} + 0.0571 \text{ cc} = 1.0443 \text{ cc} \\
 & \text{therefore, apparent porosity} = \frac{(1.1423 - 1.0443)}{1.1423} \times 100 \\
 & \quad = 0.098/1.1423 = 8.58\%
 \end{aligned}$$

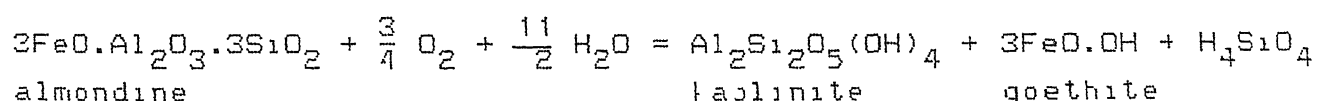
It is obvious that similar parameters for weathering can be worked out for the measured porosity values of other samples.

4.3 Comparison of Sandstone at Kusum Sarovar with Konark Temple Khondalite

The Kusum Sarovar sandstone as well as Konark Temple Khondalite, both are silicate rich rock. However, the mode of weathering is different for these two rocks.

Khondalite used in Konark temple is mainly a quartz - garnet - sillimanite gneiss. It is the presence of highly unstable mineral garnet (almondine) decaying to goethite and kaolinite which is causing the decay of this rock (Sharma, 1991). Being a metamorphic rock of granulite facies, the temperature and pressure of its formation are much different from the weathering environment. After weathering, there is an increase in molar volume of weathered product of khondalite as shown below.

The weathering of almondine can be expressed as



Molar volume of almandine garnet (\bar{V}_{ag}) = $498/4.25 = 117.18$

Molar volume of goethite (\bar{V}_{goe}) = $89/4.28 = 20.79$

Molar volume of laolinite (\bar{V}_l) = $258.17/2.60 = 99.30$

Here, one mole of almandine weathers to 3 moles of goethite and 1 mole of laolinite.

thus, % change in molar volume ($\Delta\bar{V}$) = $\frac{[(3\bar{V}_{go} + \bar{V}_l) - \bar{V}_{ag}]}{\bar{V}_{ag}} \times 100$

$$= \frac{[(3 \times 20.79 + 99.30) - 117.18]}{117.18} \times 100$$

$$= \frac{161.67 - 117.18}{117.18} \times 100 = \frac{44.49}{117.18} \times 100 = 37.97 \%$$

Therefore, a part of the weathering product must be leached away to create porosity in the weathered rock. For example, Sharma (1991) concluded that the measured porosity of 7.13 % of khondalite can be achieved if the original rock has quartz : garnet = 3 : 1 and it weathers to such an extent that 70 % - 80 % garnet is decayed and the fraction of laolinite and goethite retained are 0.50 and 0.10 respectively. The weathering index (X_d) of this particular rock was between 0.66 to 0.77. However, in case of sandstone, the molar volume of weathering product decreases after weathering as discussed earlier. Hence, with the estimated quartz to feldspar ratio (F_Q) and the fraction of feldspar weathered (F_{Fw}), the measured porosity (n) can once again be achieved only after leaching a part of the laolinite produced.

CHAPTER 5

CONCLUSION

This project was taken up with the objective of outlining fundamental aspects of decay of Bansipaharpur sandstone which contains mainly quartz and feldspar. During mineralogical investigation and subsequent laboratory studies, following conclusions were drawn :

- (i) The sandstone in its stratigraphic position belongs to Precambrian Lower Delhi - Upper Aravalli boundary.
- (ii) The rock contains quartz to feldspar weight ratio around 2:1, which was estimated from the ratio of characteristic X-ray peaks of these two minerals. This conclusion was broadly supported by microscopic texture.
- (iii) Although minor amounts of illite, pyrophyllite (?) and goethite are present in weathered rock, the decay of sandstone can be essentially depicted as a kaolinisation reaction :
$$2 \text{ K-feldspar} + 2\text{H}^+ + 9\text{H}_2\text{O} = \text{kaolinite} + 4\text{H}_4\text{SiO}_4 + 2\text{K}^+$$
- (iv) The observed red spots in some samples of light coloured sandstone are probably a product of selective oxidation of dissolved iron by interstitial water.
- (v) The weathering model based on above kaolinisation reaction and developed through a computer program on the lines of the earlier work of Sharma (1991) indicated that the measured porosity of 7.17 to 8.83 could have been produced if the sandstone with average quartz to

feldspar ratio equal to 2:1 weathered in such a way that 35-40 weight percent feldspar decayed and fraction of kaolinite retained was 0.7- 0.8. The weathering index (X_d) of the rock on a 0 - 1 scale was 0.22 to 0.38.

- (vi) Weathering index (X_d) calculated from these mineralogical parameters could be correlated with physical properties. For example, with higher X_d (more weathered rock), Apparent Specific Gravity decreased while Water Absorption alongwith Apparent Porosity showed a progressive increase. At the two sites of Kusum Sarovar and Bansipaharpur quarry, the rocks showed different values of X_d indicating a variation in degree of weathering. This is probably controlled by mineralogical and climatological factors.
- (vii) There is a basic difference in decay of khondalite and sandstone, although both are silicate - rich rocks. For example, the decay product of sandstone showed a spontaneous loss of volume whereas a volume increase takes place for weathering of khondalite. On the other hand, for both rocks, the measured porosity can be achieved only when a part of weathering product is leached away.

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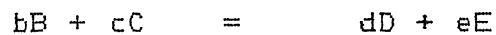
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APPENDIX - I

Construction of Thermodynamic Stability Diagram.

It is assumed that mineral - water reactions approach equilibrium in the weathering environment.

For a reversible reaction



the equilibrium constant (K) is defined as :

$$K = \frac{a_D^d \cdot a_E^e}{a_B^b \cdot a_C^c}$$

where a = activity or effective concentration of the species taking part in the reaction.

= 1, for pure minerals and liquid H₂O.

Under standard conditions (298.16° K) and 1 atmosphere pressure), Gibbs, free energy (ΔG_r^0) :

$$\Delta G_r^0 = -RT \ln K$$

$$\text{or, } \Delta G_r^0 = -2.303 RT \log K$$

$$= \sum \Delta G_f^0 \text{ product} - \sum \Delta G_f^0 \text{ reactant}$$

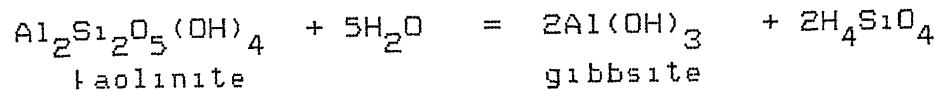
At 25° C,

$$\Delta G_r^0 = -1.364 \log K \quad (\text{in k Cal})$$

$$= -5.707 \log K \quad (\text{in kJ})$$

Stability diagrams can be constructed with logarithmic axes showing a_{K^+}/a_{H^+} and a_{HSi_4} . The boundaries of the stability diagrams for the system K₂O - Al₂O₃ - SiO₂ - H₂O are drawn [Fig.4.10] by calculating equilibrium constants for the following reactions. The Gibbs free energy values used to calculate equilibrium constants of these reactions have been taken from Drever, J.I. (1988) listed in Table I.1.

(a) Kaolinite-Gibbsite boundary.



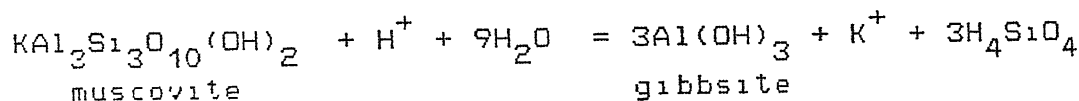
$$\begin{aligned}\Delta G_r^0 &= \sum \Delta G_f^0 \text{ product} - \sum \Delta G_f^0 \text{ reactant} \\ &= [2 \cdot \Delta G_{\text{gibb}}^0 + 2 \cdot \Delta G_{\text{H}_4\text{SiO}_4}^0] - [\Delta G_{\text{fao1.}}^0 + 5 \cdot \Delta G_{\text{H}_2\text{O}}^0] \\ &= [2 \times (-1151) + 2 \times (-1316.6)] - [(-3800) + 5 \times \\ &\quad (-237.13)] \\ &= -2302 - 2633.2 + 3800 + 1185.65 \\ &= 50.45 \text{ kJ/mol.}\end{aligned}$$

$$\rightarrow \log K = -\frac{50.45}{5.707} = -8.84$$

$$\text{and } K = \frac{a_{\text{Al}(\text{OH})_3}^2 \times a_{\text{H}_4\text{SiO}_4}^2}{a_{\text{AlOol}} \times a_{\text{H}_2\text{O}}^5}$$

$$\rightarrow \frac{1}{2} \log K = \log a_{\text{H}_4\text{SiO}_4} = -4.42$$

(b) Muscovite-Gibbsite boundary.



$$\begin{aligned}\Delta G_r^0 &= [3 \cdot \Delta G_{\text{glbb}}^0 + \Delta G_{\text{I}+}^0 + 3 \cdot \Delta G_{\text{H}_4\text{SiO}_4}^0] \\ &\quad - [\Delta G_{\text{musc.}}^0 + \Delta G_{\text{H}+}^0 + 9 \Delta G_{\text{H}_2\text{O}}^0] \\ &= [3 \cdot (-1151) + (-283.27) + 3 \cdot (-1316.6)] \\ &\quad - [(-5605) + 0 + 9 \cdot (-273.13)] \\ &= 53.1 \text{ kJ/mol}\end{aligned}$$

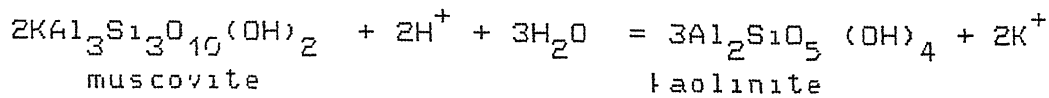
$$\text{or, } \log K = -\frac{53.1}{5.707} = -9.304$$

$$\text{and } K = \frac{a_{\text{gibb}}^3 \cdot a_{\text{H}^+} \cdot a_{\text{H}_4\text{SiO}_4}^3}{a_{\text{musc}} \cdot a_{\text{H}^+} \cdot a_{\text{H}_2\text{O}}^5}$$

$$\text{or, } \log K = \log \left(\frac{a_{K^+}}{a_{H^+}} \right) + 3 \log a_{H_4SiO_4} = -9.304$$

$$\rightarrow \log \left(\frac{a_{V^+}}{a_{H^+}} \right) = -3 \log a_{H_4SiO_4} - 9.304$$

(c) Muscovite-Kaolinite boundary.



$$\Delta G_r^0 = [3 \cdot \Delta G_{\text{f aol.}}^0 + 2 \cdot \Delta G_{\text{f +}}^0] - [2\Delta G_{\text{musc.}}^0 + 2\Delta G_{\text{H+}}^0 + 3 \cdot \Delta G_{\text{H}_2\text{O}}^0]$$

$$= [3 \times (-3800) + 2 \times (-283.27)]$$

$$-[2 \times (-5605) + 0 + 3 \times (-273.13)]$$

$$= -11966.54 + 11210 + 711.39$$

$$= -45.15$$

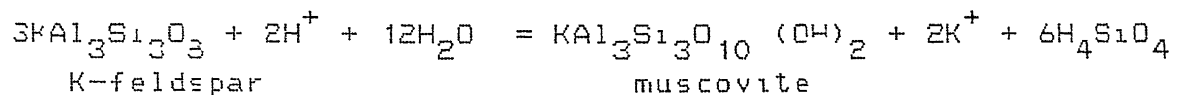
$$\log K = \frac{-45.15}{-5.707} = 7.914$$

$$\text{and } K = \frac{a_{\text{H}_2\text{O}}^3 \cdot a_{\text{H}^+}^2}{a_{\text{H}_2\text{O}}^2 \cdot a_{\text{H}^+}^2 \cdot a_{\text{H}_2\text{O}}^3} = a_{\text{K}^+}^2 / a_{\text{H}^+}^2$$

$$\therefore \log K = 2 \log (a_{K^+}/a_{H^+}) = 7.91$$

or, $\log (a_K + / a_H +) = 3.956$

(d) K-feldspar-Muscovite boundary.



$$\Delta G_r^0 = [\Delta G_{\text{musc}}^0 + 2. \Delta G_{\text{qtz}}^0 + 6. \Delta G_{\text{H}_4\text{SiO}_4}^0]$$

$$= [3. \Delta G_{K-fels}^0 + 2. \Delta G_{H^+}^0 + 12. \Delta G_{H_2O}^0]$$

$$= [-5605 + 2 \times (-283.27) + 6 \times (-1316.6)]$$

$$- [3 \times (-3767) + 0 + 12 \times (-273.13)]$$

$$= -14071.14 + 14146.56$$

$$= 75.42$$

$$\therefore \log K = -\frac{75.42}{5.707} = -13.25$$

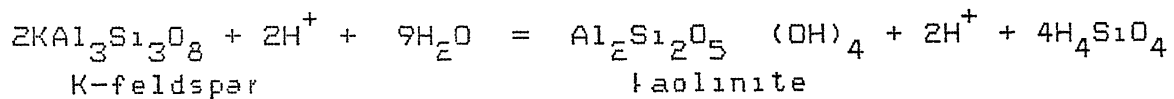
$$\text{and } K = \frac{a_{\text{musc}} \cdot a_{K^+}^2 + a_{H_4SiO_4}^6}{a_{K-fels}^3 \cdot a_{H^+}^2 \cdot a_{H_2O}^{12}}$$

$$= (a_{K^+}^2 / a_{H^+}^2) \cdot a_{H_4SiO_4}^6$$

$$\text{or, } \log K = 2 \log \left(\frac{a_{K^+}}{a_{H^+}} \right) + 6 \log a_{H_4SiO_4} = 13.25$$

$$\log \left(\frac{a_{K^+}}{a_{H^+}} \right) = -6.6077 - 3 \log a_{H_4SiO_4}$$

(e) K-feldspar-Kaolinite boundary.



$$\Delta G_r^0 = [\Delta G_{kaol}^0 + 2. \Delta G_{H^+}^0 + 4. \Delta G_{H_4SiO_4}^0]$$

$$= [2. \Delta G_{K-fels}^0 + 2. \Delta G_{H^+}^0 + 9. \Delta G_{H_2O}^0]$$

$$= [-3800 + 2 \times (-283.27) + 4 \times (-1316.6)]$$

$$- [2 \times (-3767) + 0 + 9 \times (-273.13)]$$

$$= -9632.94 + 9667.17$$

$$= 35.23$$

$$\therefore \log K = -\frac{35.23}{5.707} = -6.173$$

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$$= [2 \cdot \Delta G_{K-fels}^0 + 2 \cdot \Delta G_{H^+}^0 + 4 \cdot \Delta G_{H_2O}^0]$$

$$= [-5275 + 2 \cdot (-283.27) + 2 \cdot (-1316.6)]$$

$$= [-2 \cdot (-3767) + 0 + 4 \cdot (-273.13)]$$

$$= -8474.74 + 6482.52$$

$$= 7.78$$

$$\therefore \log K = -\frac{7.78}{5.707} = -1.363$$

$$\text{and } K = \frac{a_{\text{pyro}} \cdot a_{K^+}^2 \cdot a_{H_4SiO_4}^2}{a_{K-fels}^2 \cdot a_{H^+}^2 \cdot a_{H_2O}^4}$$

$$\text{or, } \frac{1}{2} \log K = \log \left(\frac{a_{K^+}}{a_{H^+}} \right) + \log a_{H_4SiO_4} = -0.682$$

$$\text{or, } \log \left(\frac{a_{K^+}}{a_{H^+}} \right) = (-1) \log a_{H_4SiO_4} - 0.682$$

Table I.1 Free Energy Values (kJ /mole) used in constructing
Stability Diagram at 25° C Temperature and 1
Atmosphere (Drever, 1988).

Species	Formula	ΔG_f^0 (kJ/mole)
Gibbsite	$Al(OH)_3$	-1151
Kaolinite	$Al_2Si_2O_5(OH)_4$	-3800
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	-5275
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	-5605
K-feldspar	$KAlSi_3O_8$	-3767
K^+		-283.27
H_4SiO_4 (aq.)		-1316.6
H_2O (liquid)		-237.13
H^+		0

APPENDIX II

Weathering Model for Porosity (n) and Weathering Index (X_d)

Mineralogical studies of sandstone indicate that quartz with smaller proportion of feldspar are the primary minerals. Out of these, feldspar decomposes to kaolinite. Therefore, the proportion of feldspar decreases with increasing weathering. Quartz is resistant to weathering and maintains a fairly constant proportion. As there are no clear indications of iron oxide and pyrophyllite as weathering products, they are not taken under consideration in this model.

Hence, as a quantitative measure for a two mineral model for sandstone, the weathering index or degree of decomposition is

$$X_d = \frac{N_q - N_{q0}}{1 - N_{q0}}$$

where,

$$N_{q0} = \frac{\text{volume of quartz}}{\text{volume of quartz} + \text{volume of feldspar}} \quad (\text{in fresh rock})$$

$$\text{and } N_q = \frac{\text{volume of quartz}}{\text{volume of quartz} + \text{volume of feldspar}} \quad (\text{in weathered rock})$$

X_d ranges from 0 to 1.0 with a value of 0 indicating fresh rock ($N_q = N_{q0}$) and 1 representing a totally decomposed rock ($N_q = 1$).

This calculation is equally influenced by void ratio (e). Void ratios can be interpreted in terms of X_d if it is assumed that either

- (a) no leaching occurs apart from the colloids freed during alteration of the feldspar, or
- (b) all the kaolinite and solubles are leached out together

with no loss of quartz or feldspar grains.

Neither of these two assumptions is strictly correct but the first should hold in the later stages of decomposition and the second should be roughly true in the earlier stages.

The expression for 'e' are :

$$\text{No leaching, } e = \frac{1 - N_w}{N_w + \frac{N_{qo}}{(1 - N_{qo}) \cdot X_d}}$$

$$\text{Full leaching, } e = \frac{1 - N_{qo}}{N_{qo}} \cdot X_d$$

where N_w is the volume of weathered product (kaolinite) generated by decay of unit volume of K-feldspar.

$$\text{and porosity } (n) = \frac{e}{1+e}$$

II.1 Relationship between Weight fraction of feldspar (decayed) to Weathering Index (X_d) :

Define

Weight ratio of quartz to feldspar in fresh sandstone = $F_Q : 1$

Specific gravity of quartz = 2.65

Specific gravity of feldspar = 2.58

therefore,

Volume ratio of quartz to feldspar in fresh sandstone

$$\begin{aligned} = \frac{V_Q}{V_F} &= \frac{\left(\frac{\text{weight fraction of quartz to feldspar } (F_Q)}{\text{specific gravity of quartz}} \right)}{\left(\frac{1}{\text{specific gravity of feldspar}} \right)} \\ &= 0.974 F_Q : 1 \quad \dots (1) \end{aligned}$$

and

Volume ratio of quartz to feldspar in weathered sandstone

$$= \frac{0.974 F_Q}{0.974 F_Q + (1 - F_{Fw})} \quad \dots (1v)$$

(from eqn. (11))

Now,

$$X_d = \frac{N_q - N_{qo}}{1 - N_{qo}} = \frac{\frac{0.974 F_Q}{0.974 F_Q + (1 - F_{Fw})} - \frac{0.974 F_Q}{0.974 F_Q + 1}}{1 - \frac{0.974 F_Q}{0.974 F_Q + 1}}$$

Using values of N_q and N_{qo} from equations (11i) and (1v).

$$X_d = \frac{0.974 F_Q [0.974 F_Q + 1 - 0.974 F_Q - (1 - F_{Fw})]}{0.974 F_Q + (1 - F_{Fw})}$$

$$X_d = \frac{0.974 F_Q F_{Fw}}{(1 + 0.974 F_Q) - F_{Fw}}$$

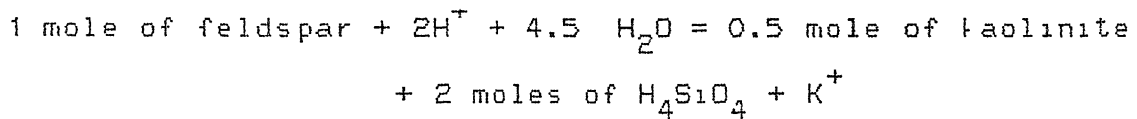
11. 2 Generation of porosity by process of decay ;

The porosity of weathered rock may increase because

(1) the molar volume of weathered product generated is less than that of decaying mineral.

(11) part of weathered product is leached away.

The simplified balanced equation for weathering of one mole of feldspar is :



e = void ratio

therefore,

$$e = \frac{\text{volume of voids } (V_v)}{\text{volume of solids } (V_s)}$$

where,

$$V_v = \text{Volume of voids} = V_F - (V_{Fu} + V_w)$$

$$V_F = \text{Volume of feldspar in fresh rock}$$

$$V_{Fu} = \text{Volume of undecomposed feldspar in weathered rock}$$

$$V_w = \text{Volume of weathering product (kaolinite)}$$

$$V_{Fu} = V_F - (1 - F_{Fw})$$

$$V_w = N_w \cdot (V_F - V_{Fu}) = N_w \cdot V_F \cdot V_{Fw}$$

$$= V_F \cdot V_{Fw} \cdot N_w$$

where,

$$N_w = \text{Volume of weathered product (laolinite) generated}$$

$$\text{by decay of unit volume of feldspar}$$

$$= R_t \times (\text{volume of 0.5 mole of laolinite})$$

where,

$$R_t = \text{fraction of total moles of laolinite which is}$$

$$\text{retained}$$

therefore,

$$N_w = \frac{R_t \times \left(\frac{1}{2} \times \frac{\text{Molecular weight of laolinite}}{\text{Specific gravity of laolinite}} \right)}{\left(\frac{\text{Molecular weight of feldspar}}{\text{Specific gravity of feldspar}} \right)}$$

where,

$$\text{Molecular weight of laolinite} = 258.172$$

$$\text{Specific gravity of laolinite} = 2.60$$

$$\text{Molecular weight of K-feldspar} = 278.35$$

$$\text{Specific gravity of K-feldspar} = 2.58$$

therefore,

$$N_w = 0.4602 \cdot R_t$$

$$\text{also, } V_v = V_F \cdot F_{Fw} - N_w \cdot V_F \cdot F_{Aw}$$

$$\text{or, } V_v = V_F \cdot F_{Fw} (1 - N_w)$$

$$\text{and, Volume of solids}$$

$$V_s = V_Q + V_{Fu} + V_w$$

$$= V_Q + V_F \cdot (1 - F_{Fw}) + N_w \cdot V_F \cdot F_{Fw}$$

therefore,

$$e = \frac{V_v}{V_s} = \frac{V_F \cdot F_{Fw} \cdot (1 - N_w)}{V_Q + V_F - V_F \cdot F_{Fw} \cdot (1 - N_w)}$$

or,

$$e = \frac{(1 - N_w) \left[\frac{1}{(1 - F_{Fw}) \cdot V_F + V_Q} - \frac{1}{V_F + V_Q} \right]}{\frac{1}{(1 - F_{Fw}) \cdot V_F + V_Q} - (1 - N_w) \left[\frac{1}{(1 - F_{Fw}) \cdot V_F + V_Q} - \frac{1}{V_F + V_Q} \right]}$$

dividing the numerator and denominator by

$$(V_F + V_Q) \cdot ((1 - F_{Fw}) \cdot V_F + V_Q)$$

$$e = \frac{(1 - N_w) \left[\frac{V_Q}{(1 - F_{Fw}) \cdot V_F + V_Q} - \frac{V_Q}{V_F + V_Q} \right]}{\frac{V_Q}{(1 - F_{Fw}) \cdot V_F + V_Q} - (1 - N_w) \cdot \left[\frac{V_Q}{(1 - F_{Fw}) \cdot V_F + V_Q} - \frac{V_Q}{V_F + V_Q} \right]}$$

Multiplying numerator and denominator by V_Q

$$\begin{aligned} e &= \frac{(1 - N_w) \left[\frac{(V_Q/V_F)}{(1 - F_{Fw}) \cdot V_F + V_Q} - \frac{(V_Q/V_F)}{V_F + V_Q} \right]}{\frac{(V_Q/V_F)}{(1 - F_{Fw}) \cdot V_F + V_Q} - (1 - N_w) \cdot \left[\frac{(V_Q/V_F)}{(1 - F_{Fw}) \cdot V_F + V_Q} - \frac{(V_Q/V_F)}{V_F + V_Q} \right]} \\ &= \frac{(1 - N_w) \left[\frac{0.974 F_Q}{0.974 + (1 - F_{Fw})} - \frac{0.974 F_Q}{0.974 F_Q + 1} \right]}{\frac{0.974 F_Q}{0.974 F_Q + 1 - F_{Fw}} - (1 - N_w) \left[\frac{0.974 F_Q}{0.974 F_Q + 1 - F_{Fw}} - \frac{0.974 F_Q}{0.974 F_Q + 1} \right]} \end{aligned}$$

from equation (1)

$$\begin{aligned} e &= \frac{(1 - N_w) (N_q - N_{q0})}{N_q - (1 - N_w) (N_q - N_{q0})} \\ &= \frac{(1 - N_w)}{N_w - \frac{N_q - N_{q0}}{N_q - N_{q0}} - 1} \end{aligned}$$

dividing numerator and denominator by $N_q - N_{q0}$

$$e = \frac{(1 - N_w)}{N_w + \frac{N_q - N_q + 1}{N_q - N_{q0}} q_0} = \frac{(1 - N_w)}{N_w + \frac{N_{q0}}{N_q - N_{q0}}}$$

and

$$\text{apparent porosity (n)} = \frac{e}{1 + e}$$

$$n = \text{fn } (F_{Fw}, F_Q, R_t)$$

where,

F_Q = weight fraction of quartz to feldspar in fresh sandstone

F_{Fw} = fraction of feldspar which has weathered

R_t = fraction of total moles of kaolinite retained

In summary, the porosity (n) of weathered sandstone is a function of three variables namely, F_Q , F_{Fw} and R_t . For a given n, F_Q and R_t , the X_d and F_{Fw} can be calculated.

On the basis of this relationship, a computer program was written in "C" language on HP - 9000 system to estimate weathering index (X_d) and porosity (n) for different values of F_{Fw} , F_Q and R_t . The program is given in Appendix III.

APPENDIX III

Computer Program for Weathering Model

```

#include <stdio.h>
#include <math.h>
#define MOWTQ 60 09
#define SPGRQ 2 65
#define MOWTF 278 35
#define SPGRF 2 52
#define MOWTK 252 172
#define SPGRK 2 60
#define X SPGRF/SPGRQ
#define Y (0 5)*((MOWTK/SPGRK)/(MOWTF/SPGRF))
FILE *f1,
char filename[12], answer, reply, choice,
float fq, ffld, ffc, wfo, rk, wf, xd, nw, nqo, nq, e, n,
/*fq=wt of qtz in fresh rock*/
/*ffld=wt of fels in fresh rock*/
/*ffc=Fq, rk=Rk, wf=Fw*/
/*nw=Hw, nqo=Nqo, nq=Nq, e=e*/

main()
{
    printf("Enter the output filename | \n"),
    scanf("%s", filename),
/*    if ((f1=fopen(filename, "a"))==NULL)
    {
        /*
        f1=fopen(filename, "w"),
/*    }
    Data_input(f1),
    fclose (f1),
}
Data_input(fptr)
FILE *fptr,
{
    int wrc = 0, k,
    int rlc = 0, j,
    int ffc = 0, i,
    float ffc [20], rks [20], wfs [40],
    printf("Enter wt fractions of      to fels in fresh rock |\n"),
    do
        scanf ( "%f", &ffc [ffc++]),
    while (ffc [ffc-1] >= 0),
    printf("Enter the set Rk values |\n"),
    do
        scanf ( "%f", &rks [rkc++]),
    while (rks[rkc-1] >= 0),
    printf("Enter wt fractions of fels in weath rock |\n"),
    do {

```

```

        scanf ("%f", &wfs[wfc++]),
    } while (wfs[wfc-1] >= 0),
    -- ffqc, -- rkq, -- wfc,
    for (i = 0, i < ffqc, ++ i) {
        ffq = ffqs[i],
        for (j = 0, j < rkq, ++ j) {
            rk = rks[j],
            fprintf(fp, "fract of kaol retained . % .6f", rk),
            fprintf(fp, "%e", "\n"),
            fprintf(fp, "fract of qtz to fels : % .6f", ffq),
            fprintf(fp, "%e", "\n"),
            fprintf(fp, "%e", "\n"),
            for (k = 0, k < wfc, ++ k) {
                wf = wfs[k],
                wf /= 100,
                calculate(),
                fprintf(fp, "wf=% .2f      Xd=/ .6f      n=% .6f\n", wf*100, xd, n*100),
            }
        }
    }
}
calculate()
{
    xd=((X*wf*ffq)/((1+X*ffq)-wf)),
    nw=r1+r,
    nqo=((X*ffq)/((X*ffq)+1)),
    nq=((X*ffq)/((X*ffq)+(1-wf))),
    e=((1-nw)/(nw+(nqo/(nq-nqo)))),
    n=(e/(1+e)),
}

```